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MOISTURE-SENSITIVITY OF DIELECTRIC CONSTANT OF JUTE AND COTTON*

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(Received for publication, August 4, 1952)

ABSTRACT. The effect of moisture on the dielectric constant of jute and cotton for th raw and chemically treated forms have been studied. The moisture-sensitivity of their electric constant is found to be different from one another but when dry, they have sensibly e same value of dielectric constant. Attempts have been made to explain this difference their behaviour.

INTRODUCTION

The primary object with which the present work was started was to design electric moisture meter for use in jute industry. From a preliminary survey the effect of moisture on the different electrical properties of jute fibres, a udy of moisture-sensitivity of their dielectric constant was found promising for e purpose. For a comparative study, it was also thought of interest to extend r observations to chemically treated samples of jute fibres, as well as to raw d chemically treated fibres of cotton. Measurements have been made therefore t only on samples of native raw jute and cotton, but also on five samples of emically treated jute and one sample of chemically treated cotton. The emically treated jute samples include three alkali-treated samples prepared by ing 1%, 12.5% and 17.5% NaOH solutions at room temperature, one lignified and one holocellulose sample prepared by the use of usual chlorite thod. The chemically treated cotton sample was a mercersied one using .5% NaOH solution also at the room temperature.

perimental fibre-condenser.

After many trials, a condenser as shown in figure 1, was suitably designed contain a given weight of fibres at various conditions of relative humidities. was essentially of parallel-plate type. The plates are circular brass discs of meter 6.15 cm. and thickness 0.45 cm. and are nickel-plated to give a smooth ning surface. On one side of the plates, brass rods, about 15 cm. in length 1 1.3 cm. in diameter, are fixed centrally at right angles to the plane of the tes. On these rods threads are cut. The plates along with the rods are ed face to face inside a horizontal pyrex glass tube of length 17.8 cm. Its ide diameter almost coincides with the diameter of the condenser plates. It fitted with inlet and outlet tubes at its ends for the purpose of circulating of desired humidities through it. Each end of the glass tube is closed by ans of a flange and rubber gasket. At the back of each flange a nut, fixed an ebonite hand-wheel, is fitted over the brass rod and its plate can be

* Communicated by Prof. P. C. Mahanti.

moved inwards and outwards within the glass tube, as required by mean of the hand-wheel. The plates are prevented from rotating during their movement

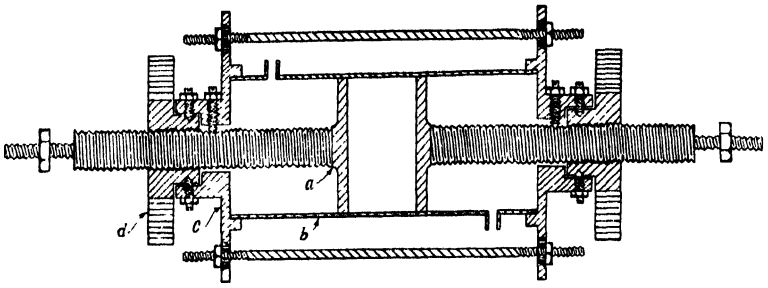


FIG. 1.

(a) Plate with rod. (c) Flange and Gasket.
(b) Glass tube. (d) Ebonite hand wheel

by means of a keyway fitting with the nut. Two binding screws at the ends of the two rods serve as the terminals of the condenser. The assembly is then suitably mounted in a horizontal position on a wooden frame.

In subsequent measurements, the plates were kept at 0.45 cm. apart and the capacity of the condenser under this condition with air as the medium, as measured on the Schering bridge, was about 8.5 $\mu\mu f$. while that calculated from its dimensions was about 6.1 $\mu\mu f$. For the purpose of this investigation, the parasitic capacity 2.4 $\mu\mu f$, as obtained from these data was assumed to remain constant throughout all measurements.

Method of packing.

Since dielectric constant depends on the alignment of the fibres with respect to the field, it was necessary to ensure a random packing of the fibres in the condenser. For this purpose the fibres were cut into small lengths mixed with a few drops of water and made into a plug which was inserted into the condenser for conditioning. The effect of air could not altogether be eliminated and hence the measured values would be lower than the actual dielectric constants of the fibres.

Conditioning of fibres.

The arrangement for conditioning the fibres in the condenser is as shown in figure 2. A given weight of fibres, 3.5 gm., was cut into small pieces and uniformly packed in the space between the condenser plates which were next screwed out to allow the inlet and outlet tubes to be introduced between them. The towers were filled with sulphuric acid-water mixtures of appropriate concentration for obtaining a particular relative humidity. Air was bubbled through the acid solutions and allowed to pass through the fibres and finally drawn out through the outlet tube of the condenser, a combined force/exhaust pump being used for the purpose. The object of having three towers was to ensure

that the concentration of the acid mixture in the tower nearest to the condenser remained practically constant during the period of circulation of air. About 4-5 hours of continuous flow at the rate of 2 litres per minute was found sufficient for the attainment of equilibrium humidity in the fibres. To avoid

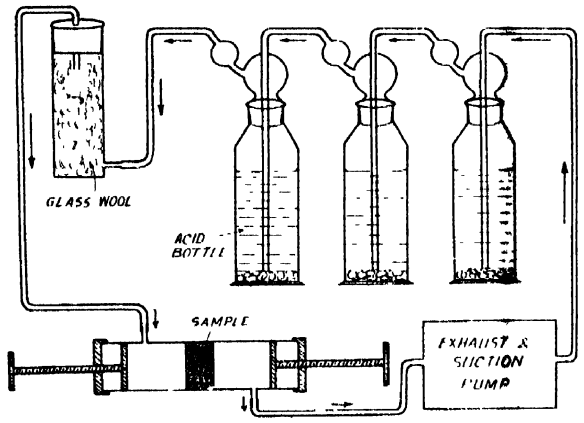


Fig. 2

uncertainty about the equilibrium point the fibres were conditioned for 20 hours by circulating humidified air continuously overnight at the end of which period the inlet and the outlet tubes of the condenser were closed, so that outside air could not disturb the condition of the fibres. The condenser plates were then brought closer to a distance of 1.35 cm. between their outer edges. To eliminate the effect, if there be any, of the previous history of the samples regarding the moisture absorption every sample was first conditioned at 0% relative humidity and its dielectric constant was measured, and the measurements continued after progressively increasing the relative humidity of conditioning and then similarly diminishing it so that a complete cycle of absorption and desorption could be taken.

Measurement of dielectric constant.

The circuit diagram of the bridge used is as shown in figure 3. All measurements were made at a frequency of oscillation of 2 Kc/sec. by the usual method of substitution. A standard air condenser C was placed in the fourth arm and the fibre condenser was inserted across the variable standard condenser C_s. Balance was obtained by adjusting the power factor in the second arm and the capacity C_s in the third arm. Under this condition

$$\frac{C}{C_{s1}+C_1} = \frac{R_1}{R_2} \qquad (1)$$

(C = capacity of the standard air condenser, C_{s1} = capacity of the variable condenser C_s, C_f = capacity of the fibre condenser. R_1 and R_2 are impedances in the ratio arms 1 and 2 respectively.)

The fibre condenser was removed and again balance was obtained when

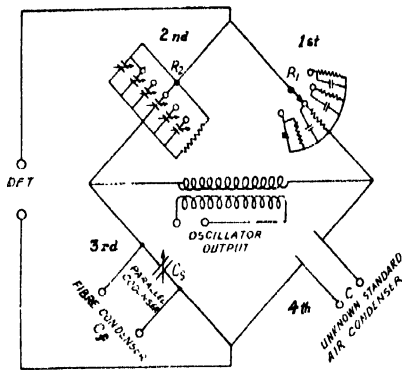
$$\frac{C}{C_s} = \frac{R_1}{R_2} \qquad (2)$$

(C_s = capacity of the variable condenser at the balance point.)

From (1) and (2)

$$C_f = C_s - C_{s_1} \qquad \ldots \quad (3)$$

From the observed value of C_f, the net capacitance (C'_f) of the glass condenser at a given value of moisture content was obtained by making allowance



SCHERING CAPACITANCE BRIDGE

Fig. 3

for its parasitic capacitance and the value of dielectric constant was evaluated from the following relation,

$$K = \frac{11{\cdot}31\ C'_f t}{A},$$

where C'_f is given in $\mu\mu F$, t is the thickness of the sample in cm. and A is the area of the condenser plates in cm.^{2}

Special care was taken to ensure the constancy of the frequency of oscillation during a measurement, for which purpose a stabilisation period of nearly half-an-hour was allowed to pass before a reading was taken. In order to check the accuracy of measurements, capacities of known laboratory standard capacitors were measured and it was found that the error did not exceed 1%. Replicate measurements with a given weight of fibres in the condenser confirmed the reproducibility of the results.

Effect of pressure.

It was considered important to investigate if the dielectric constant of a sample undergoes any appreciable variation when the separation between the electrodes for a given weight of the sample is slightly different from the value at which they were normally kept. It was found that the variations in the distance between the condenser plates over a range 0.35 - 0.60 cm. and hence the corresponding pressure variations, did not affect appreciably the dielectric constant of a sample, the maximum change being about 3% at the highest value of its moisture content.

EXPERIMENTAL RESULTS

TABLE I

Jute samples

Sample	Adsorption results			Desorption results		
	% R.H.	% M.C.	K	% R.H.	% M.C.	K
Raw jute	0	0	1·80	73	16·5	3·80
	27	5·0	1·83	60	12·0	2·80
	37	6·2	1·93	51	9·7	2·10
	55	9·1	2·12	42	8·0	1·94
	60	10·0	2·18	39	7·5	1·89
	70	11·8	2·54	29	6·5	1·82
	79	13·7	3·60	2	0·1	1·80
	100	31·2		—	—	—
Holo-cellulose	0	0	1·83	66	10·5	8·84
	28	4·5	1·93	49	7·3	4·59
	51	6·6	3·12	33	6·0	2·26
	62	7·8	5·60	19	4·0	2·06
	69	8·9	8·30	0	0	1·71
	100	27·0		—	—	—
Delignified jute	0	0	1·85	61	13·1	4·27
	25	5·6	1·89	50	11·0	2·70
	42	8·2	2·05	38	9·2	2·60
	56	10·0	2·58	28	7·5	2·15
	71	12·0	4·37	14	4·5	2·06
	100	35·0		0	0	1·83
17·5% NaOH jute	0	0	1·80	87	21·5	2·66
	25	5·2	1·90	71	15·5	2·48
	38	6·9	1·98	51	11·0	2·29
	52	8·5	2·10	36	9·0	2·05
	65	10·5	2·19	19	6·0	1·90
	75	12·6	2·27	10	3·5	1·85
	100	28·2	3·60	0	0	1·81
12·5% NaOH jute	0	0	1·87	81	18·5	2·81
	26	5·2	2·00	70	14·1	2·41
	36	6·2	2·04	56	10·5	2·20
	51	8·0	2·15	42	8·2	2·07
	63	9·7	2·26	24	6·5	1·98
	85	15·6	2·66	10	3·5	1·88
	100	29·5	4·10	0	0	1·87
15% NaOH jute	0	0	1·88	82	19·0	3·15
	23	5·0	1·98	67	13·2	2·51
	36	6·2	2·05	48	9·0	2·16
	45	7·2	2·12	35	7·6	2·04
	61	9·5	2·32	20	6·5	1·97
	76	12·5	2·58	0	0	1·88
	88	17·5	3·30			
	100	30·0	4·42			

(C_s = capacity of the variable condenser at the balance point.)

From (1) and (2)

$$C_f = C_s - C_{s1} \qquad \ldots \quad (3)$$

From the observed value of C_f, the net capacitance (C'_f) of the fibre condenser at a given value of moisture content was obtained by making allowance

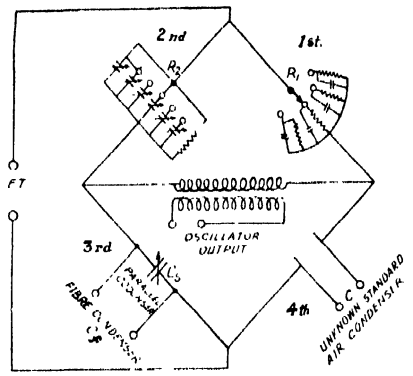


Fig. 3

for its parasitic capacitance and the value of dielectric constant was evaluated from the following relation,

$$K = \frac{11{\cdot}31\ C'_f t}{A},$$

where C'_f is given in $\mu\mu F$, t is the thickness of the sample in cm. and A is the area of the condenser plates in cm.^{2}

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Effect of pressure.

It was considered important to investigate if the dielectric constant of a sample undergoes any appreciable variation when the separation between the electrodes for a given weight of the sample is slightly different from the value at which they were normally kept. It was found that the variations in the distance between the condenser plates over a range 0.35 - 0.60 cm. and hence the corresponding pressure variations, did not affect appreciably the dielectric constant of a sample, the maximum change being about 3% at the highest value of its moisture content.

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Raw jute	0	0	1·80	73	16·5	3·80
	27	5·0	1·83	60	12·0	2·80
	37	6·2	1·93	51	9·7	2·10
	55	9·1	2·12	42	8·0	1·94
	60	10·0	2·18	39	7·5	1·89
	70	11·8	2·54	29	6·5	1·82
	79	13·7	3·60	2	0·1	1·80
	100	31·2		--	——	
Holo-cellulose	0	0	1·83	66	10·5	8·84
	28	4·5	1·93	49	7·3	4·59
	51	6·6	3·12	33	6·0	2·26
	62	7·8	5·60	19	4·0	2·06
	69	8·9	8·30	0	0	1·71
	100	27·0		—	——	
Delignified jute	0	0	1·85	61	13·1	4·27
	25	5·6	1·89	50	11·0	2·70
	42	8·2	2·05	38	9·2	2·60
	56	10·0	2·58	28	7·5	2·15
	71	12·0	4·37	14	4·5	2·06
	100	35·0		0	0	1·83
17·5% NaOH jute	0	0	1·80	87	21·5	2·66
	25	5·2	1·90	71	15·5	2·48
	38	6·9	1·98	51	11·0	2·29
	52	8·5	2·10	36	9·0	2·05
	65	10·5	2·19	19	6·0	1·90
	75	12·6	2·27	10	3·5	1·85
	100	28·2	3·60	0	0	1·81
2·5% NaOH jute	0	0	1·87	81	18·5	2·81
	26	5·2	2·00	70	14·1	2·41
	36	6·2	2·04	56	10·5	2·20
	51	8·0	2·15	42	8·2	2·07
	63	9·7	2·26	24	6·5	1·98
	85	15·6	2·66	10	3·5	1·88
	100	29·5	4·10	0	0	1·87
NaOH jute	0	0	1·88	82	19·0	3·15
	23	5·0	1·98	67	13·2	2·51
	36	6·2	2·05	48	9·0	2·16
	45	7·2	2·12	35	7·6	2·04
	61	9·5	2·32	20	6·5	1·97
	76	12·5	2·58	0	0	1·88
	88	17·5	3·30			
	100	30·0	4·42			

TABLE II

Cotton samples

Sample	Adsorption results			Desorption results		
	% R.H.	% M C	K	% R.H.	% M.C.	
Raw cotton ..	0	0	1·80	70	9·5	5·00
	7	2·0	1·80	57	7·5	3·70
	22	3·1	1·86	50	6·5	3·09
	37	4·0	2·15	43	5·6	2·61
	52	4·8	2·69	35	4·8	2·40
	62	6·0	4·11	28	4·2	2·05
	74	8·0	4·88	18	3·2	1·92
	100	—	—	0	0	1·83
Mercerised cotton	0	0	1·85	74	16·9	5·93
	26	6·0	1·88	63	13·6	3·66
	45	8·5	2·21	46	10·5	2·74
	59	10·3	2·58	29	7·7	2·10
	75	13·0	3·89	14	4·5	1·85
	100	35·0	—	0	0	1·83

TABLE III

Air dielectric

Adsorption results		Desorption results	
% R.H.		% R.H.	
0	1·00	100	1·35
30	1·05	90	1·17
80	1·10	80	1·10
90	1·17	30	1·05
100	1·35	0	1·00

DISCUSSION

The variation of dielectric constant with relative humidity of conditioning for the various samples of jute and cotton is shown in figure 4 which includes also the results of measurements on the experimental condenser with air alone as medium between its plates. It will be noted that for a given change in the

relat · humidity, the change in the dielectric constant of air is much smaller than · it of the fibres. This is perhaps due to the more dispersed state of the

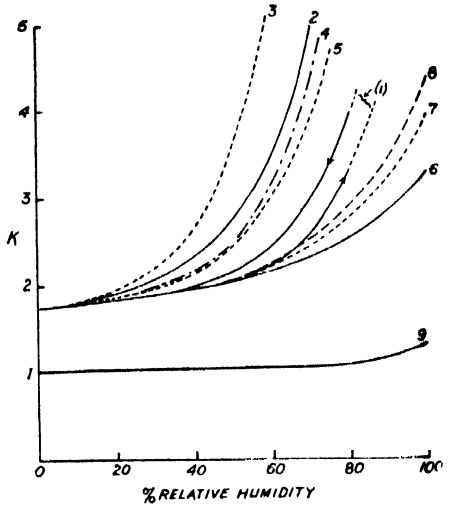

Fig. 4

Curve (1) — Jute (raw)
„ (2) — Cotton (raw)
„ (3) — Holocellulose
„ (4) — Delignified jute
„ (5) — Mercerised cotton
„ (6) — 17·5% NaOH treated jute
„ (7) — 12·5% „ „ „
„ (8) — 1% „ „ „
„ (9) — Air condenser

molecules of water vapour in the former case. The main features of the results are :

(*a*) For a given sample, the dielectric constant at a particular relative humidity, depends upon whether it is conditioned by absorption or desorption, the dielectric constant in the latter case being higher, as can be seen from curve (1).

(*b*) The dielectric constant of jute is lower than that of cotton at any value of relative humidity although its moisture content corresponding to a given relative humidity is higher.

(*c*) Mercerisation or alkali treatment decreases the dielectric constant of jute and cotton.

(*d*) Delignification increases the dielectric constant of jute to a value nearing that for cotton at any value of relative humidity.

(*e*) The dielectric constant is sensibly the same for all dried samples of jute and cotton, irrespective of being raw or chemically treated.

The curves showing the variation of dielectric constant with moisture content of the different samples are given in figure 5. It may be noted that unlike the dielectric constant—relative humidity curve, the dielectric constant —moisture content curve is the same for both increasing and decreasing values of moisture content of conditioning of a sample.

It is now almost an established idea that the dielectric properties of fibres and polymeric substances in general can be explained in terms of an oscillation and relaxation spectrum. The former arises mainly out of electron and atom polarizations while the latter is the result of polarization on account of orientation of the molecules or their polar parts or displacement of ions, the translational or rotational diffusion as the case may be, requiring a supply of a statistical distribution of activation energy. The dielectric constant at frequencies of the applied field within the range 10^3—10^9 c/sec. can be regarded as largely due to

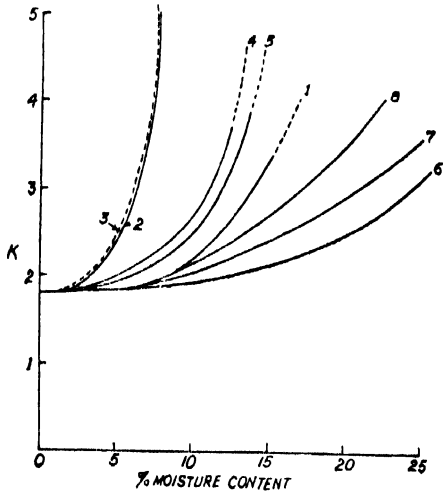

Fig. 5

polarization as a result of ionic displacement or dipolar orientation, whereas, that at higher frequencies due to electron and atom polarization. The dielectric properties, such as the dielectric constant and the loss angle, of inhomogeneous materials consisting of conducting or semi-conducting particles dispersed in an insulator can be explained with the help of Maxwell-Wagner equations and their subsequent modifications due to Sillars (1937) which relate these properties in terms of volume fractions, dielectric constants and conductivities of the components. Sillars has indicated that the shape of the conducting particles has a profound influence upon the dielectric constant. As for instance, a system having prolate (needle-like) particles will give a much higher dielectric constant than that with particles of oblate (lens-like) shape, the unique axis of both pointing toward the direction of the field.

The total quantities of moisture in fibres can be broadly regarded as composed of (1) bound and (2) free moisture. The small quantity of chemically bound moisture and that absorped in the localised sites forming a unimolecular layer, both form the bound moisture ; on the other hand, the free moisture inside fibres may be either (1) dispersed molecules in the multimolecular layers of adsorption and bound by the same force as between the molecules of liquid water or (2) liquid water in the capillaries of varying size and shape, or (3) both. Direct measurement of the relative proportions of bound and free moisture is rather difficult. For cotton, however, Peirce (1929) has

calculated these quantities from probalility considerations. Since the ratio of dielectric constant of water and that of the fibre substance is very high (about 80 : 5) and the dielectric constant of water decreases with decrease in the freedom of movement of the molecules, one would except that the dielectric constant will be very sensitive to the presence of water and, of the two states of water inside the fibres, the free moisture would affect it by a greater amount. The similarity in the nature of the curves as given in figure 4 and that showing the relation between free moisture and relative humidity for cotton, due to Peirce, also points to such calculation. The increase in the dielectric constant with moisture content can therefore be regarded as due to an increase in the amount of free moisture and is not likely to be the result of a decrease in the air content of the composite dielectric with swelling.

The fibre samples used in the the present investigation undoubtedly possess varying proportions of polar groups in the hydroxyls and the carboxyls of the constituents as well as in the associated water molecules, the moment and the freedom of motion of the dipole in each sample being different. It is therefore reasonable to expect their dielectric properties to be widely different on account of the difference in the dipole orientations resulting from the application of the alternating field. Figure 4 shows, however, that the fibres have almost the same dielectric constant at 0% relative humidity which suggests that in this case, the dipole mechanism is not effective. Since the frequency of the applied field, 2 Kc/sec., can be regarded as low, being about the lowest limit at which polarization due to ionic displacement or dipolar orientation is likely to occur, it will not be altogether without reason to exclude such a possibility. A small difference in the dielectric constant values for the various samples may arise out of a possible difference in the density of the fibre substances. It should be mentioned that the almost identical dielectric constant values for the various dry fibres may be due to the low order of accuracy of measurement in this region. If the effect of the intervening air could be eliminated by subjecting the fibres to a high pressure the dielectric constant values and therefore, the order of accuracy of measurement would certainly be higher as a result of which small differences, if there were any, between the dielectric constant values for the individual fibre sample would be revealed.

Accepting that the increase in the dielectric constant is due to an increase in the free moisture content as pointed out above and that the structure of the fibres is not likely to alter progressively with moisture absorption so as to effect increase either in the freedom of movement of the polar groups, or in the substance density, the observed relation between dielectric constant and moisture content can be explained by applying either Wagner model or its modification due to Sillars. Since the whole of moisture absorbed in the fibres is not in the free state, the volume fractions of free moisture need to be calculated. Using the Peirce's data for cotton the free moisture content at different relative humidities for jute can be deduced, if it is assumed that the proportions of bound moisture in jute and cotton are in the ratio of their non-crystalline constituents, 1.56, as indicated by Sen and Hermans (1949) disregarding the

content of the fibres. Assuming that lignin took part in the formation of the pores in jute and somehow blocked the cellulosic region having finer pores, its removal would lead to a fibrous material with finer pores which in respect of the dielectric properties would therefore approach cotton fibres.

The action of alkali on both jute and cotton can be regarded as to increase the bound moisture content on account of swelling due to which a greater number of reactive groups, hydroxyl or carboxyl, is likely to be available for moisture absorption. Simultaneously, fibres having larger pores may also result from alkali treatment.

ACKNOWLEDGMENTS

The author acknowledges with pleasure his gratefulness to the Indian Jute Mills Association Research Institute and to its Research Director, Dr. W. G. Macmillan, for the award of a Scholarship to carry out the investigation. He is greatly indebted to Prof. P. C. Mahanti, Head of the Department of Applied Physics, and to Dr. M. K. Sen, Chief Physicist, IJMARI, for their guidance and helpful discussions during the course of the work.

REFERENCES

Harmans, P. H., 1946, Contribution to the Physics of Cellulose Fibres, Elsevier.
Macmillan, W. G., Mukherjee, R. R., and Sen, M. K., 1946, *J. Text Inst.*, **37,** T13.
Muhlethaler, K., 1949, *Biochem. Biophys. Acta*, **3,** 15.
Peirce, F. T., 1929, *J. Text. Inst.*, **20,** T133.
Roy, M. M., 1951, Ph.D. Thesis, Calcutta University.
Sen, M. K. and Harmans, P. H., 1949, *Recueil Trav. Chim. Pays—Bas*, **68,** 1079.
Sillars, R. W., 1937, *J. Inst. Elec. Eng.*, **8,** 378.
Urquhart, A. R. and Williams, A. M., 1924, *J. Text. Inst.*, **15,** T138.